Physical and Biological Effects of Sand Mining Offshore Alabama, U.S.A.

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ABSTRACT

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Physical processes and biological data were collected and analyzed at five sand resource areas offshore Alabama to address environmental concerns raised by potential sand dredging for beach replenishment. Nearshore wave and sediment transport patterns were modeled for existing and post-dredging conditions, with borrow site sand volumes ranging from 1.7 to 8.4×10^6 m³. Wave transformation modeling indicated that minor changes will occur to wave fields under typical seasonal conditions and sand extraction scenarios. Localized seafloor changes at borrow sites are expected to result in negligible impacts to the prevailing wave climate at the coast. For all potential sand excavation alternatives at borrow sites offshore Alabama, maximum variation in annual littoral transport between existing conditions and post-dredging configurations was approximately 8 to 10%. In general, increases or decreases in longshore transport rates associated with sand mining at each resource area amounted to about 1 to 2% of the net littoral drift, distributed over an approximate 10 km stretch of shoreline. Because borrow site geometries and excavation depths are similar to natural ridge and swale topographic characteristics on the Alabama Outer Continental Shelf, infilling rates and sediment types are expected to reflect natural variations within sand resource areas.

Impacts to the benthic community are expected from physical removal of sediments and infauna. Based on previous studies, levels of infaunal abundance and diversity may recover within 1 to 3 years, but recovery of species composition may take longer. Western areas can be expected to recover more quickly than eastern areas because of opportunistic life history characteristics of numerically dominant infauna west of Mobile Bay.

ADDITIONAL INDEX WORDS: *Bathymetric change, benthic, infauna, sediment transport, shoreline change, wave modeling.*

INTRODUCTION

The coastal zone is a unique geological, physical, and biological area of vital economic and environmental value. HOUSTON (1995, 2002) discusses the value of beaches to America's economy and their maintenance via beach nourishment. In addition, MILLER (1993) stresses the importance of coastal and marine tourism as the world's largest industry, noting its continual rise in economic importance over the past 50 years. Beaches not only are the dominant component of most coastal economies, but also provide protection against storm winds and waves. Coastal community master plans are being developed and revised to address concerns associated with storm protection, population growth, recreation, waste disposal and facilities management, and zoning (WILLIAMS, 1992). Often, these management issues are confounded by natural coastal processes, particularly coastal erosion and storm winds and waves. Replenishing beaches with sand from coastal and nearshore sources as protection for community infrastructure has increased in direct relation to population growth. As sand mining depletes coastal and nearshore borrow areas, alternate sources of beach fill must be

located and knowledge of the environmental consequences of offshore sand mining must be expanded. In many cases, sand extraction from the Outer Continental Shelf (OCS) may prove environmentally preferable to nearshore borrow areas because potential changes to waves and currents resulting from dredging large quantities of sand from the seafloor may be more pronounced in shallow water.

This paper discusses some physical and benthic biological aspects of a study whose purpose and objectives were specified by the U.S. Department of the Interior, Minerals Management Service (MMS). The study purpose was to address environmental concerns associated with potential sand mining operations at five OCS sand resource areas offshore Alabama for beach replenishment. Four objectives addressed the study purpose, including: (1) document potential modifications to waves due to offshore sand mining at proposed borrow sites; (2) evaluate impacts of offshore sand mining and consequent beach replenishment in terms of potential alterations to sediment transport patterns, sedimentary environments, and local shoreline processes; (3) characterize benthic ecological conditions in and around five sand resource areas using existing information and data collected from field surveys; and (4) evaluate infaunal assemblages and assess potential effects of offshore sand mining on these organisms,

including an analysis of recolonization periods and success following dredging. Because monitoring surveys of actual sand mining operations were not to be conducted, the assessment of potential infaunal effects was based only on benthic infaunal characterization field surveys and existing literature. This paper focuses on physical and infaunal effects from sediment removal. It also provides statistical properties of local infaunal assemblages that will assist in designing future sand resource area monitoring programs. Other potential impacts from sediment suspension/dispersion (turbidity) and deposition are addressed in BYRNES *et al.* (1999).

STUDY AREA

The study area was located within the inshore portion of the continental shelf, seaward of the Federal-State OCS boundary and within the Alabama Exclusive Economic Zone (EEZ) (Figure 1). The seaward limit of the study area was defined by the 30°N latitude line. The project area was located within the east Louisiana-Mississippi-Alabama Shelf. The continental shelf surface within the study area is relatively broad and featureless west of the Mobile Bay entrance; however, the Alabama shelf east of the entrance channel contains many northwest-southeast trending shoreface sand ridges, as well as other shoals.

Five potential sand resource areas, located at least 4.5 km seaward of the shoreline, were defined within the study area

through a Federal-State cooperative agreement between the MMS and Geological Survey of Alabama. PARKER *et al.* (1993, 1997) characterized the sand resource potential for each area based on surface sediment samples and vibracore data. HUMMELL and SMITH (1995, 1996) provided detailed geologic information on Sand Resource Area 4 to supplement existing information, identifying a specific low-relief shoal in the southeast quadrant of the sand resource area as a prime borrow site.

REGIONAL SETTING

The Alabama continental shelf can be divided into two regions based on geomorphology and hydrology (PARKER *et al.*, 1997). The eastern shelf extends from the Alabama-Florida state boundary to Mobile Pass (Figure 1). The western shelf extends from Mobile Pass to the Alabama-Mississippi State boundary at Petit Bois Pass. The large ebb-tidal delta at Mobile Pass is approximately 16 km wide, extends about 10 km offshore (HUMMELL, 1990), and separates the two regions.

The eastern portion of the study area is characterized by numerous shelf and shoreface sand ridges and swales that trend northwest to southeast (Figure 1; McBRIDE and BYRNES, 1995; PARKER *et al.,* 1997). Ridges are considered shoreface-attached and shoreface-detached (PARKER *et al.,* 1992), and form oblique angles to the shoreline that open to the east. Ridges average 6 km in length and range from 1 to
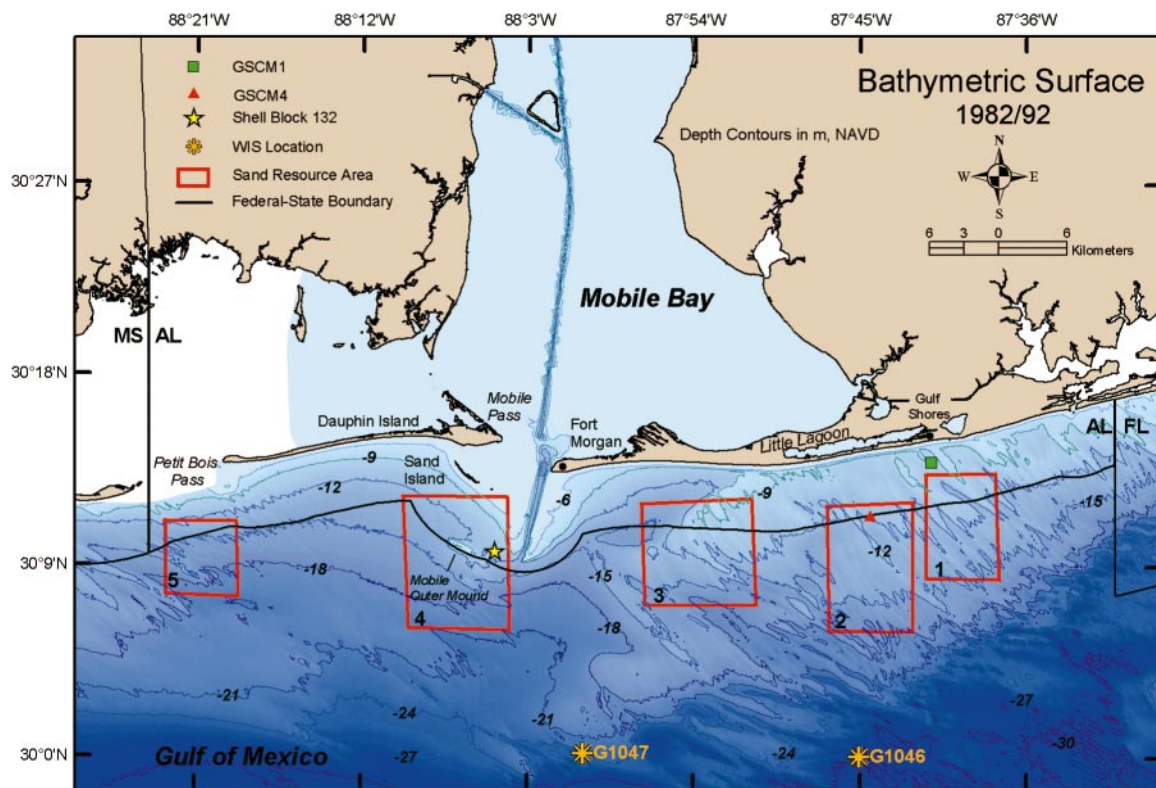

Figure 1. Location diagram illustrating sand resource areas, current measurement locations, WIS stations, and the Federal-State boundary relative to 1982/92 bathymetry.

11 km long. Ridge widths range from 1 to 4 km with spacing between ridges varying between 1 and 7 km. Ridge side slopes average about 1°, and relief above the surrounding sea-floor ranges from 1 to 5 m (MCBRIDE and BYRNES, 1995). Shoreface-attached or shoreface-detached ridges generally form opening angles with the east-west trending shoreline of 30 to 60°. Shoals formed as pre-Holocene paleotopography generally are oriented nearly perpendicular to the shoreline, reflecting their fluvial origin.

The western half of the study area, from Mobile Pass west to Petit Bois Pass, has relatively few geomorphic features compared with the eastern part of the study area. Shoals associated with deposition near the entrances to Mobile Pass and Petit Bois Pass are prominent; however, the shelf seaward of Dauphin Island is smooth and concave. Marginal shoals of the ebb-tidal delta are quite shallow to the west of Mobile Pass. HUMMELL (1990) and DOUGLASS (1994) discuss the significance of these features to sediment transport patterns along the shoreline of eastern Dauphin Island. Overall, the shelf surface in the western half of the study area slopes at about 1.5 m/km.

METHODS

Existing literature and data describing the physical and benthic biological environments in the study area were analyzed to evaluate potential consequences of offshore sand mining activities. In addition, physical and benthic characterization field surveys were conducted to fill information gaps present in existing data sets according to the following methods.

Physical Processes

Waves

The U.S. Army Corps of Engineers (USACE) Wave Information Study (WIS) results (1976 to 1995) for offshore Alabama (WIS Stations G1047 and G1046) provided a detailed description of the regional wave climate used to develop representative wave spectra. Rather than selecting the most common wave heights and directions as model input, WIS information was summarized into average seasonal wave conditions and spectra. Directional and energy spectra also were estimated from previous storm spectra to simulate conditions for a 50-year event. A storm surge value for the estimated 50-year event was included in the wave modeling simulation to represent increased water level experienced during the passage of a large storm. Surge values for 25

storms impacting the study area between 1772 and 1969 were used in an extremal analysis to estimate a height of 3 m for a 50-year storm surge.

The spectral wave transformation model REF/DIF S (KIRBY and ÖZKAN, 1994) was used to evaluate changes in wave propagation across the Alabama continental shelf relative to potential sand mining configurations. Differences in wave heights between existing conditions and post-dredging simulations were computed at each grid point within the model domain to document potential changes caused by specific sand mining scenarios. Proposed sand extraction volumes and sediment characteristics for borrow sites in Sand Resource Areas 1 through 4 are listed in Table 1. Each borrow site was numerically excavated to simulate potential impacts of offshore dredging on physical processes. Sand extraction from Area 5 was not simulated because the location of potential sand deposits was not well suited for beach replenishment needs in coastal Alabama. Existing condition wave simulations were subtracted from post-dredging wave results so that positive (negative) differences indicated an increase (decrease) in wave height related to sand mining at each borrow site.

Currents

Two current meter data sets were used to evaluate seasonal and annual flow variations throughout the study area. Continental Shelf Associates, Inc. provided current meter observations near Area 4 for the period September 28, 1987 to October 24, 1988 (approximately 1.6 m above the seafloor in approximately 12-m water depth; HART *et al.,* 1989). The mooring was deployed west of the main ship channel in Shell Block 132, due east of the dredged material disposal mound known as Mobile Outer Mound (Figure 1). A series of five moorings were deployed near Areas 1 and 2 by the Environmental Protection Agency (EPA) for the period March 1986 to March 1987. Mooring 1M (GSCM1) had mid-depth observations collected in approximately 5-m water depth. Mooring 4 (GSCM4) was located in approximately 10-m water depth with observations recorded at near-surface (4S) and near-bottom (4B).

Field measurements of currents within Sand Resource Areas 2 and 4 were conducted in May and September of 1997 to observe spatial flow variations in eastern and western portions of the study area. Four surveys were completed; one survey per season in each of Areas 2 and 4. Each survey recorded measured currents during an approximate 12-hour period. A survey transect grid was created with transect lines

Table 1. *Sand resource characteristics at potential borrow sites in resource areas offshore Alabama.*

Resource Area	Surface Area ($\times 10^6$ m²)	Sand Volume ($\times 10^6$ m³)	Excavation Depth (m)	D10 (mm)	D50 (mm)	D90 (mm)
1	1.94	5.8	3	0.93	0.25	0.18
2	0.57	1.7	3	0.44	0.22	0.14
3	1.19	4.7	4	0.44	0.27	0.14
4	2.80	8.4	3	0.50	0.34	0.20
5	Resource area location not suited for beach replenishment needs in the Alabama coastal zone					

D10 = grain diameter above which 10% of the distribution is retained; D50 = median grain diameter; D90 = grain diameter above which 90% of the distribution is retained.

traversed repeatedly throughout the survey (BYRNES *et al.,* 1999). Currents were measured using an acoustic doppler current profiler (ADCP) mounted rigidly to a small vessel. The ADCP collected high-resolution measurements of the vertical structure of current flow beneath the instrument transducer. Repeating transects at regular time intervals throughout a complete tidal cycle documented spatial and temporal variation in current structure. Measurements of flow variations throughout the region were analyzed with long-term historical current data to enhance understanding of flow characteristics in the Alabama sand resource areas.

Sediment Transport

Three independent sediment transport analyses were completed to evaluate physical environmental impacts due to offshore sand mining. First, historical sediment erosion and accretion trends were quantified with sequential shoreline and bathymetric surveys to document long-term sediment movement (*e.g.,* BYRNES and HILAND, 1995). Historical map compilation and analysis procedures for surveys of coastal Alabama are documented in BYRNES *et al.* (1999). Second, annualized sediment infilling rates were estimated for each borrow site using analytical expressions developed by MADSEN and GRANT (1976) that incorporate information on wave orbital velocities, local current measurements, and sediment

textural characteristics at borrow sites. Third, numerical techniques were developed to use nearshore wave information derived from REF/DIF S to evaluate changes in longshore sediment transport patterns (beach erosion and accretion) resulting from potential offshore sand mining activities. This involved application of a wave-induced current model where the depth-averaged continuity equation and depth-averaged x and y momentum equations were integrated and time averaged (WINER, 1988; RAMSEY, 1991).

Benthic Infaunal Characterization Surveys

Sampling Design

During each benthic infaunal characterization field survey (May and December 1997), 20 grab samples (one per station) for infauna and sediment grain size were collected inside and adjacent to each of the five sand resource areas (Figure 2). Station depths ranged from a minimum of 8 m to a maximum of 23 m, though most were located at depths between 10 and 20 m. An unaligned grid approach was used to provide uniform coverage of target populations (GILBERT, 1987). To achieve uniform sampling coverage, 4 × 4 grids (=16 cells) were placed over figures of each sand resource area. For Areas 1, 2, 3, and 5, the 16-cell grid was placed over a map of the entire sand resource area in Federal waters. Because the
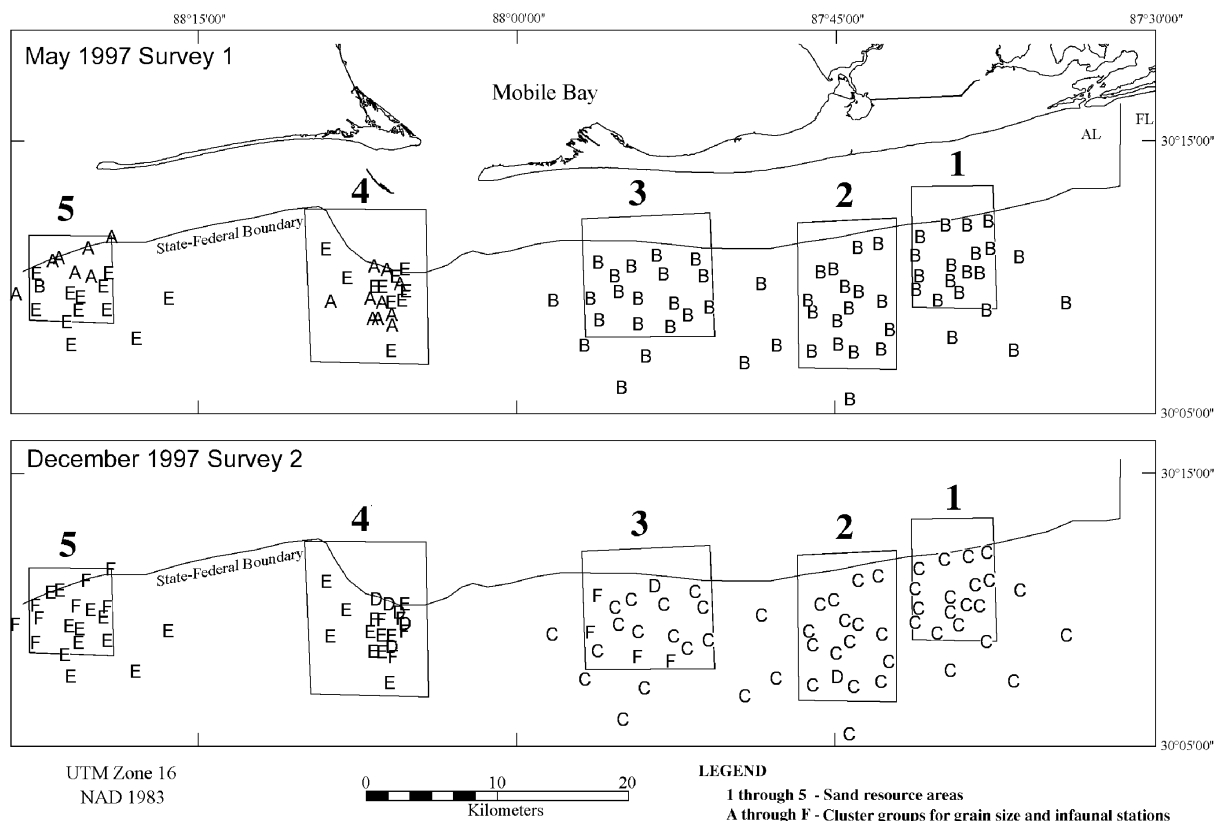

Figure 2. Distribution of Station Groups A through F resolved from cluster analysis and multidimensional scaling of infaunal data collected from five offshore Alabama sand resources areas during May and December 1997.

borrow site within Area 4 was very localized based on surficial sediment samples and subsurface core data of PARKER *et al.* (1993, 1997) and HUMMELL and SMITH (1995, 1996), the 16-cell grid was placed over this specific target site within Area 4. To achieve independence, one sampling station then was placed using randomly generated coordinates within each grid cell of each sand resource area. Randomizing within grid cells eliminated biases that could be introduced by unknown spatial periodicities in the sampling area. All station locations then were pre-plotted on maps from PARKER *et al.* (1993, 1997) and HUMMELL and SMITH (1996). A differential global positioning system was used to navigate the survey vessel to all sampling stations. Temperature, conductivity, and dissolved oxygen were measured near bottom with a portable Hydrolab unit near the northern (depths ranged from 10 to 16 m) and southern (depths ranged from 14 to 19 m) limits of each sand resource area (n = 2/area/survey).

Sediment Grain Size

One grab sample was taken with a Smith-McIntyre grab at each pre-plotted sediment/infaunal sampling station, for a total of 100 samples per survey (n = 20/area/survey). A subsample (about 250 g) of sediment for grain size analyses was removed from each grab sample with a 5-cm diameter acrylic core tube, placed in a labeled plastic bag, and stored on ice. In the laboratory, grain size analyses were conducted using combined sieve and hydrometer methods according to recommended American Society for Testing Materials procedures. Samples were washed in demineralized water, dried, and weighed. Coarse and fine fractions were separated by sieving through a U.S. Standard Sieve Mesh No. 230 (62.5 μm). Sediment texture of the coarse fraction was determined at 0.5-phi intervals by passing sediment through nested sieves. Weight of materials collected in each particle size class was recorded. Boyocouse hydrometer analyses were used to analyze the fine fraction (<62.5 μm). A computer algorithm determined size distribution and provided interpolated size information for the fine fraction at 0.25-phi intervals. Percentages of gravel, sand, and fines (silt + clay) were recorded for each sample.

Infauna

After removing the sediment sample from the grab, the remaining grab sample was sieved through a 0.5-mm sieve for infaunal analyses. Infaunal samples were preserved in 10% formalin with rose bengal stain. In the laboratory, organisms were identified to lowest practical taxon and counted.

Univariate summary statistics including number of taxa, number of individuals, density, Shannon's index of diversity (H') (PIELOU, 1966), Pielou's index of evenness (J') (PIELOU, 1966), and Margalef's index of species richness (D) (MARGALEF, 1958) were calculated for each sampling station. Station means of these summary statistics were then calculated for each sand resource area.

Spatial and temporal patterns in infaunal assemblages were examined using several multivariate techniques, including non-metric multidimensional scaling (MDS), cluster analysis, similarity percentage breakdown (SIMPER), and analysis of similarities (ANOSIM). These analyses were performed on a similarity matrix constructed from a raw data matrix consisting of taxa and samples (station-survey). The data matrix was constructed using taxa that collectively contributed to 95% of the total abundance over all samples. This produced a data matrix of 135 taxa by 200 stations. To weight the contributions of common and rare taxa, raw counts of each individual infaunal taxon in a sample (n) were transformed to logarithms [$\log_{10}(n+1)$] prior to similarity analysis. A sample similarity matrix was generated using the Bray-Curtis similarity index (BRAY and CURTIS, 1957). This matrix was clustered using the group averaging method that describes mean levels of similarity between groups of stations (FIELD *et al.*, 1982). Cluster analysis was followed by MDS ordination of the similarity matrix to corroborate cluster results. Species accounting for observed assemblage differences among groups and within groups of samples were identified using the SIMPER procedure, which determines the average contribution of each species to characterizing a sample group or discriminating between pairs of sample groups (CLARKE, 1993). The hypothesis of no difference in assemblage composition among sand resource areas or between surveys was examined using a two-way ANOSIM procedure (CLARKE, 1993). Working from the similarity matrix, ANOSIM calculates a test statistic, R, that reflects differences between sand resource areas contrasted with differences among stations within sand resource areas, ignoring surveys, and conversely, differences between surveys contrasted with differences among stations within surveys while ignoring sand resource areas. The significance of the calculated R values was tested against null distributions of R generated by 999 random permutations of the data matrix. These analyses (MDS, SIMPER, ANOSIM) were performed with the PRIMER v5 package (CLARKE and GORELY, 2001).

The extent to which station groups formed by cluster analysis and ordination of infaunal data could be explained by environmental variables was examined by canonical discriminant analysis (CDA) (SAS INSTITUTE, INC. STAFF, 1989), which identifies the degree of separation among pre-defined groups of variables in multivariate space. Environmental variables included survey (categorical), water depth, percent gravel, percent sand, and percent fines.

RESULTS

Physical Processes

Wave Transformation Modeling

Wave refraction and diffraction generally result in an uneven distribution of wave energy along the coast that affects sediment transport in a region. Wave spectra developed for the Alabama coast illustrated that all seasonal waves propagate from east-to-west. Wave transformation modeling results provided information on wave propagation across the continental shelf to the shoreline, revealing areas of wave energy convergence and divergence. These results also supplied input for nearshore circulation and sediment transport models.

Existing Conditions. For a typical spring season along the

shoreline east of Mobile Pass and Fort Morgan, areas of wave convergence and divergence were caused by irregular bathymetry and the southwest-oriented seaward extending shoal near Area 3 (Figure 1). Wave energy converged in regions where bathymetric contours were aligned shore perpendicular, as waves refracted relative to bathymetry. Summer, fall, and winter season results indicated similar patterns of wave convergence and divergence. There were no visible differences in wave height patterns for different seasons. The winter season was slightly more energetic (wave heights approximately 0.2 to 0.3 m greater). However, spring and fall simulations were almost identical, with only a slight variation in directional spreading.

Seaward of Dauphin Island for a typical spring season, significant wave focusing was evident behind the Mobile Outer Mound dredged material placement area (shoal feature west of Mobile Pass channel; Figure 1). Wave refraction around this feature created increased wave heights of approximately 0.25 to 0.5 m in the lee of the shoal and decreased wave heights adjacent to the feature. Wave focusing caused by Mobile Outer Mound produced an increase in energy that advanced toward Sand Island, the western subaerial portion of the Mobile Pass ebb-tidal delta. Sand Island offers a natural protective buffer against wave action for the eastern end of Dauphin Island, as indicated by a wave shadow zone behind the island. A similar increase in wave energy was evident near the western end of Dauphin Island as bathymetric contours redirected wave energy toward the western terminus of the island.

Simulations for the winter season produced results that were very similar to results discussed for a typical spring season. Minor differences occurred due to increased significant wave height and subtle changes in the frequency and directional spread of the incident wave spectrum (BYRNES et al., 1999). Slightly greater increases in wave energy were located in areas where wave shoaling was identified for the spring season. During a typical summer season, average wave heights were reduced significantly (approximately 0.3 to 0.5 m) in regions where wave shoaling was apparent. Wave focusing caused by Mobile Outer Mound and regions near the dredged navigation channel was less severe. Fall season results were similar to results for a typical summer season, except wave heights during fall were 0.5 to 0.6 m higher than summer.

Storm wave propagation patterns were similar to those documented for seasonal trends. However, during a 50-year storm, Mobile Outer Mound concentrated a 4.0- to 4.5-m wave field on southeastern Sand Island, and a significant reduction in wave height was evident adjacent to this area. Wave shoaling in other areas (*e.g.,* dredged navigation channel) appeared less important when considering larger storm waves. Wave approach directions were modified farther offshore because large storm waves interacted with the seafloor in deeper water than average seasonal waves.

Existing Conditions Versus Post-Dredging Results. Figure 3 illustrates wave height differences for the spring season seaward of the shoreline east of Fort Morgan. Wave height modifications were greatest for borrow sites seaward of eastern Alabama beaches, with maximum changes in wave height approaching 0.3 to 0.4 m. The increase in wave height was due to borrow site location relative to the shoreline and borrow site size and orientation. A maximum wave height increase of 0.2 to 0.4 m along the western edge of Areas 1, 2, and 3 resulted from the large sediment extraction scenarios for a typical spring season simulation. A maximum decrease of 0.4 m was evident in the lee of the dredged borrow sites. The shadow zone behind the Area 2 borrow site was more concentrated due to borrow site orientation. However, energy dissipated as waves advanced toward the shoreline, and negligible increases in wave height (0.1 m or less) were observed along the coast.

During summer, fall, and winter, patterns of wave modifications were comparable. Maximum increases/decreases in wave height were slightly smaller ($\pm$0.2 to 0.3 m) than observed during spring. For fall simulations, modifications to the wave field were less consolidated due to the less focused wave approach direction. During summer and winter, a small area of increased wave height observed at the western edge of the borrow site within Area 3 appeared to propagate to the shoreline (at approximately 412,500 Easting; 3,344,000 Northing; Figure 3). However, changes at the shoreline were negligible. Overall, potential shoreline impacts caused by simulated dredging at all offshore sand borrow sites under normal wave conditions were small relative to wave propagation under existing conditions.

Figure 4 illustrates a wave height difference plot between existing conditions and post-dredging simulations for the spring season offshore Dauphin Island, indicating that sand mining creates a zone of decreased wave energy behind the borrow site and increased energy adjacent to the borrow site. A maximum increase and decrease of approximately 0.2 m (11% change relative to offshore significant wave height) resulted from the sediment extraction scenario for Area 4 during a typical spring season. Increased wave energy was focused near the southwest end of Sand Island and on the eastern end of Dauphin Island. A decrease in wave energy was evident in the lee of the borrow site, and therefore reduced the magnitude of wave height focused by Mobile Outer Mound.

Winter season differences indicated a slight shift in the impact zone to the east due to variations in peak spectral wave approach. The magnitude of wave height differences was slightly smaller than illustrated for spring simulations, and the western edge of Sand Island experienced an insignificant increase in wave height (0.02 to 0.04 m). For summer season simulations, waves were smaller with shorter periods, and the directional spread was quite wide. Wave field modifications were not well-defined, and changes were negligible. Fall season model runs produced slightly larger changes in wave height differences on a portion of Sand Island; however, changes were determined to be negligible (0.05- to 0.06-m increase) relative to existing conditions.

A similar distribution of wave energy change as that indicated for seasonal results was illustrated for 50-year storm simulations (*i.e.,* wave energy reduction directly landward of the dredged area, and an adjacent increase in energy). A maximum increase in wave height of approximately 1.5 m (20% increase over offshore wave heights) and a wave height
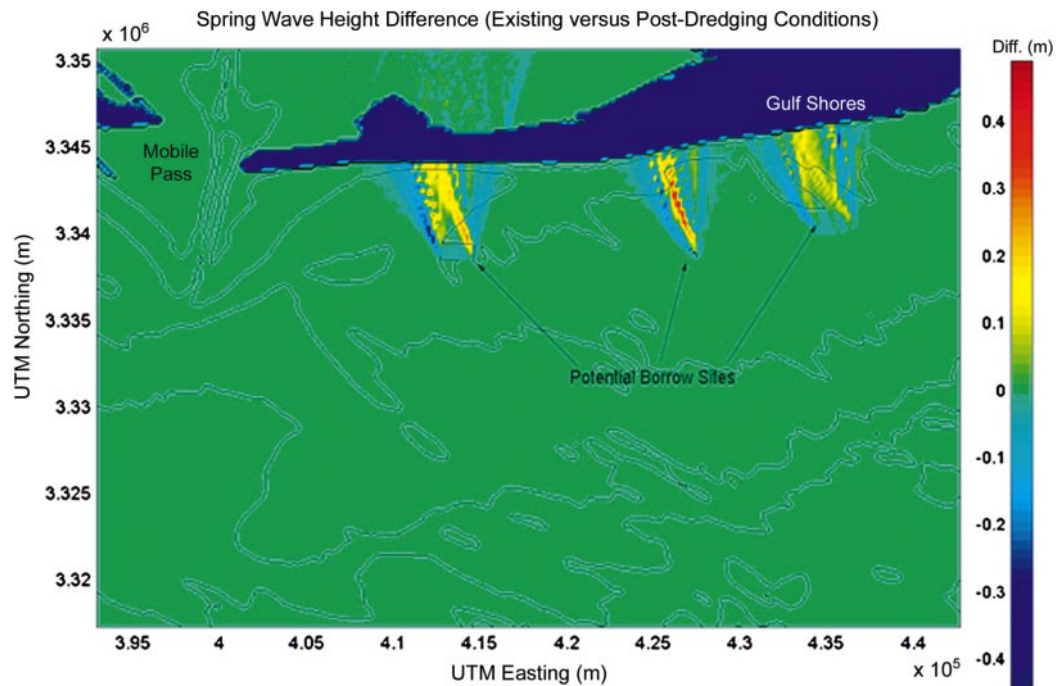
Figure 3.   Wave height modifications resulting from potential offshore mining at Areas 1, 2, and 3 for a typical spring season.
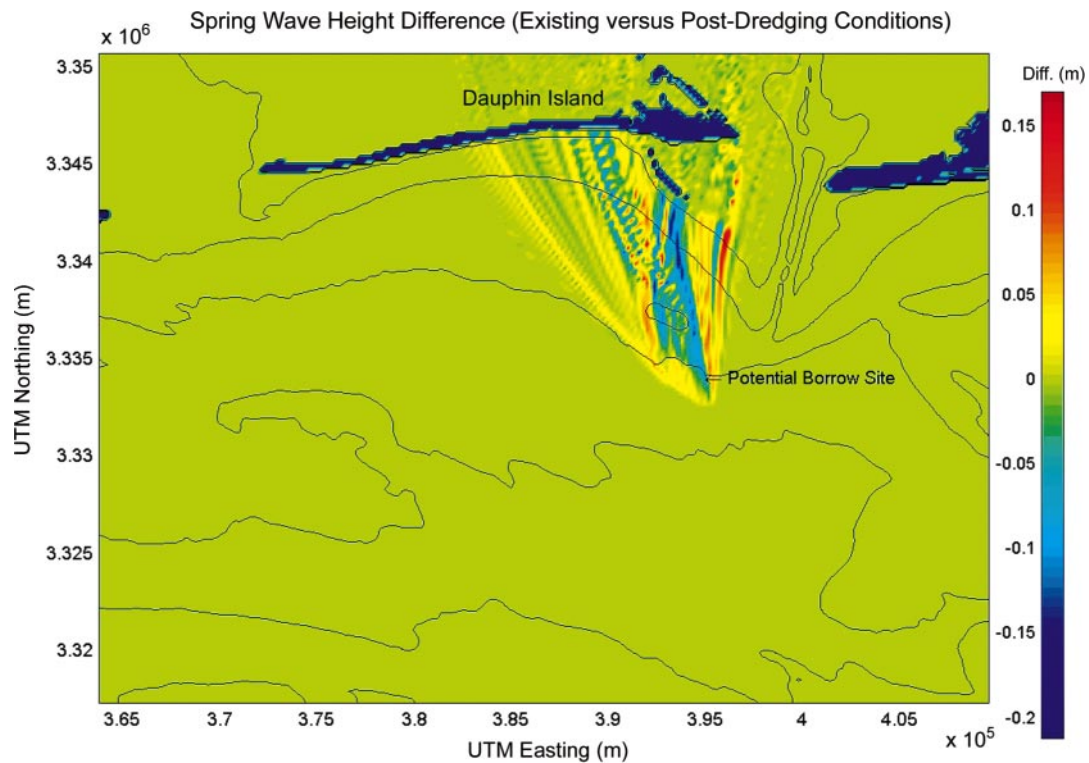

Figure 4.   Wave height modifications resulting from potential offshore mining at Area 4 for a typical spring season.

reduction of 1.5 to 2.0 m were observed in the shadow zones of borrow sites.

Currents

Temporal Variability. Near-bottom currents west of the Mobile Bay entrance (Shell Block 132 mooring) typically were oriented along a northwest-southeast axis that is parallel to bathymetric contours at the site. Strongest flow was to the southeast with 15 to 25 cm/sec speeds occurring approximately 8 to 10% of the time (Figure 5). Current speeds exceeding 25 cm/sec were observed less than 2% of the time.

Currents to the east of Mobile Bay were strongest at the surface (Mooring 4S) and weakest at the bottom (Mooring 4B). Currents also were oriented primarily in the alongshore direction. While surface flow was oriented to the west and northwest approximately 33% of the time, this westward flow was typically weaker than flow to the east. Westward flow greater than 15 cm/sec at Mooring 4S occurred approximately 5% of the time, while eastward flow exceeding 15 cm/sec occurred approximately 17% of the time. Approximately 1% of the time, eastward flow exceeded 35 cm/sec, whereas westward flow never exceeded 35 cm/sec.

Wind-driven currents were the largest contributor to overall observed currents. Analysis of historical data sets also illustrated that wind-driven currents were oriented by local bathymetric features. Thus, predominant current directions were controlled not only by the direction of alongshore wind but also by shape of the shoreline and bottom boundaries. Directional distribution of flow changed little with season and maintained a predominant orientation parallel to isobaths. Highest current speeds occurred in winter, when flows exceeding 15 cm/sec were more frequent than at other times of year. Because strong northerly winds are common in winter, while mild southerly winds are predominant in summer, wind-driven currents maintained an alongshore direction (northwest to southeast) and generally were consistent with variations in seasonal wind strength. In summer, wind-driven currents exceeded 5 cm/sec approximately 23% of the time and exceeded 15 cm/sec about 3% of the time. In winter, wind-driven currents exceeded 5 cm/sec approximately 60% of the time, 15 cm/sec 13% of the time, and greater than 25 cm/sec 3% of the time. In summer, wind-driven flow did not exceed 25 cm/sec.

Spatial Variability. Comparison of May and September ADCP surveys revealed variations in vertical structure of the water column and the influence vertical stratification had on
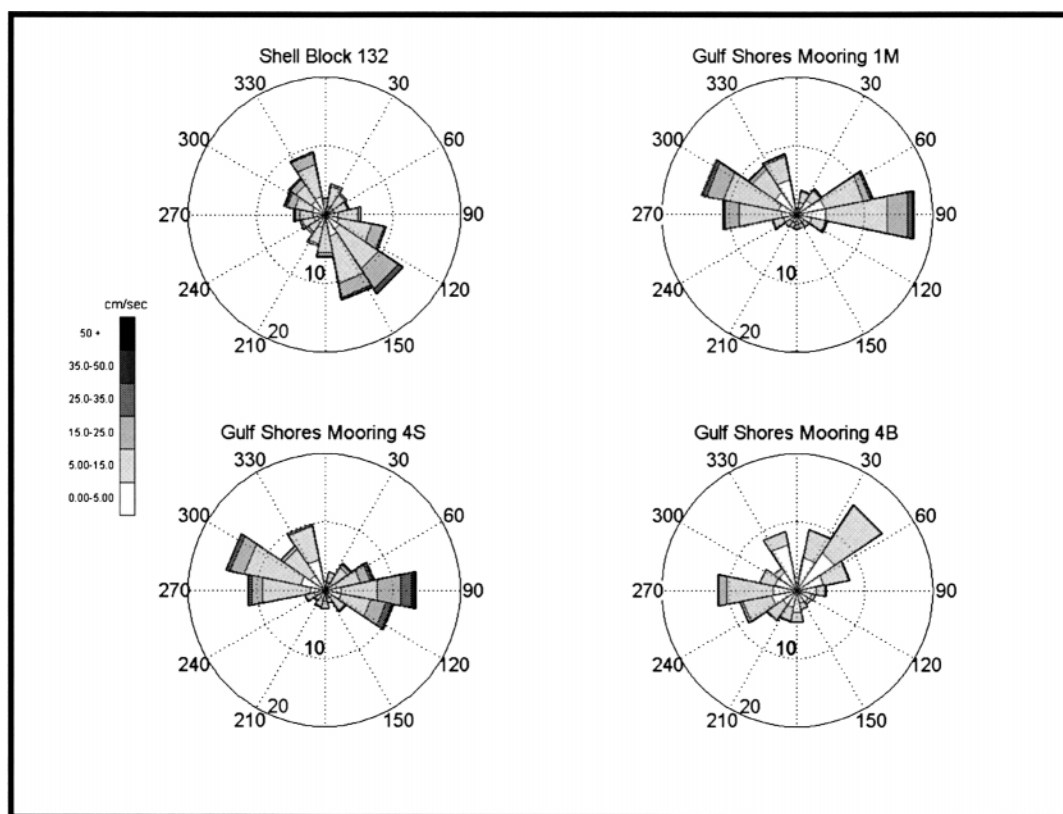

Figure 5. Rose diagrams illustrating four historical data sets of currents in the study area. Spokes of the diagram represent compass directions. Circumferential lines represent percent occurrence, with the inner annulus representing 10%, and the outside diameter representing 20% occurrence. Current speeds are represented by shading, with white (no shading) portions representing the fraction of time currents are between 0 and 5 cm/sec, and black portions indicating the percent occurrence of currents over 50 cm/sec.

the current field. East of Mobile Pass at Area 2, surface layer currents were relatively uniform during the May survey, with flows oriented north-northeast at speeds of approximately 15 to 30 cm/sec early in the day. Later in the day, surface currents shifted east-northeast and ranged from approximately 15 to 40 cm/sec. The entire surface flow field appeared oriented in a uniform direction with little horizontal directional variability. Mid-depth (10 to 35 cm/sec) and near-bottom (5 to 25 cm/sec) flows also indicated little horizontal variability.

Currents throughout Area 2 were quite uniform during the September survey as well. No significant horizontal variation was observed in the surface layer, as the flow field was uniformly directed to the east-southeast. Speeds were relatively consistent and ranged from approximately 25 to 50 cm/sec. Mean speed at the surface was approximately 40 to 45 cm/sec. Speeds in the middle layer were approximately 15 to 40 cm/sec. Near-bottom currents had slightly more directional variance, primarily due to influence of bathymetry. Mean speeds were approximately 20 cm/sec in the near-bottom layer.

During the May survey offshore Dauphin Island, vertical and horizontal flow variability at Area 4 occurred due to flow

exchange with Mobile Bay and interaction with bathymetric features. Surface and mid-layer currents observed during the survey indicated minor horizontal variation. Flow in these layers was directed primarily west to east, responding to the westerly longshore component of wind that had been blowing for the previous few days. Overall, flow in the southern (deeper) portion of Area 4 was to the east, with amplitudes of approximately 25 to 35 cm/sec (Figure 6). Flow in the northern (shallow) regions was southeast, steered by local bathymetry around Sand Island, with a similar flow magnitude as in deeper areas.

For the September survey, surface flow throughout Area 4 generally followed depth contours, with currents in deeper regions oriented to the southeast. Surface layer current speeds ranged from 40 to 50 cm/sec. Mid-layer flow had speeds of approximately 25 to 35 cm/sec, and bottom flow was weakest at approximately 15 cm/sec.

Sediment Transport

Wave transformation modeling and current measurements provided baseline coastal processes information for the study
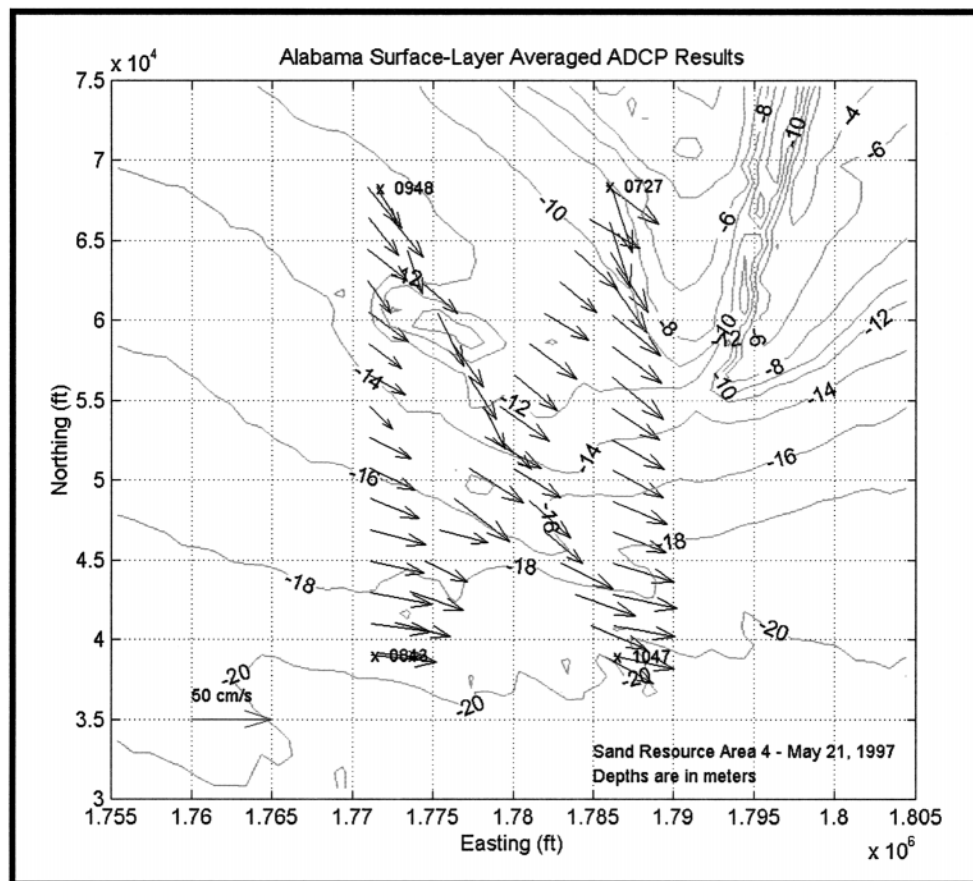

Figure 6. Vector map of observed flow patterns for Area 4; May 21, 1997 from 0727 hours to 1150 hours. Current vectors represent average flow in the surface layer (upper one-third of the water column). The numbers in each corner of the transect grid (0727, 0948, 0848, and 1047) refer to the time (hour of day) that the transect line was started.

area. However, the most important data sets for documenting physical processes impacts from offshore sand mining contain quantified changes in sediment transport dynamics resulting from potential sand extraction scenarios.

Regional Historical Trends. Regional geomorphic changes between 1917/20 and 1982/91 were documented for assessing long-term, net coastal sediment transport dynamics using shoreline and bathymetric surveys. Although these data do not provide information on potential impacts of sand dredging from proposed borrow sites, they do provide a means of verifying predictive sediment transport model results relative to infilling rates at borrow sites and net longshore sand transport rates. Between 1917/20 and 1982/91, net sediment movement was to the west throughout the Alabama coastal zone. This direction of transport was consistent with historical shoreline change trends (see BYRNES *et al.,* 1999) and dredging practice at Mobile Pass channel (disposal is always west of the channel).

At Area 1, net erosion and accretion rates associated with sand ridge migration were quite variable over short distances. Shoal migration near the sand resource area illustrated net transport to the west, but transport rates varied from 9,000 to 34,000 m³/year. Net sediment volume change at the borrow site indicated no significant movement for the period of record; however, absolute sediment volume change (erosion plus accretion) averaged about 8,500 m³/year. Although the potential for transport (and borrow site infilling) was high in this area, the average sand transport rate was consistent with other sand resource areas south and east of Fort Morgan and Gulf Shores.

Near the northern boundary of Area 2, a well-defined zone of erosion existed adjacent to a zone of deposition as a shoreface sand ridge migrated to the west under the influence of incident shelf processes (Figure 7). The zone of deposition indicated a net accumulation rate of about 6,200 m³/year, whereas the net erosion rate was calculated as about 9,100 m³/year (rates of change were normalized relative to borrow site surface area). As such, the average, long-term net transport rate for the borrow site was estimated as 7,300 m³/year. For Area 3, net erosion at the borrow site was about 585,000 m³, or about 8,800 m³/year.

West of Mobile Pass at Area 4, three specific sub-sites documented sediment deposition at 1) the potential sand borrow site, 2) Mobile Outer Mound (constructed by the USACE), and 3) the dredged material disposal area used by the USACE during channel dredging operations (Figure 7). For the sand borrow site, total sediment deposition was about 4.8 × 10⁶ m³ between 1917/20 and 1991, or about 66,000 m³/year accumulation.

Net alongshore changes in erosion and accretion, determined from seafloor changes in the littoral zone between Perdido Pass and Mobile Pass, indicated a gradient in transport to the west at about 106,000 m³/year. Variations in longshore transport are evident in patterns of change recorded on Figure 7 (alternating zones of erosion and deposition along the shoreline). It appears that areas of largest net transport existed just east of Gulf Shores where coastal erosion was greatest in the littoral zone.

Borrow Site Infilling. Predicted sediment infilling rates ranged from a maximum of 117 m³/day (42,700 m³/year) at Area 1 to a minimum of 37 m³/day (13,500 m³/year) at Area 4. Sediment that replaces sand mined from a borrow site will fluctuate based on location, time of dredging, and storm characteristics following dredging episodes. However, infilling rates and sediment types are expected to reflect natural variations that currently exist within sand resource areas. As
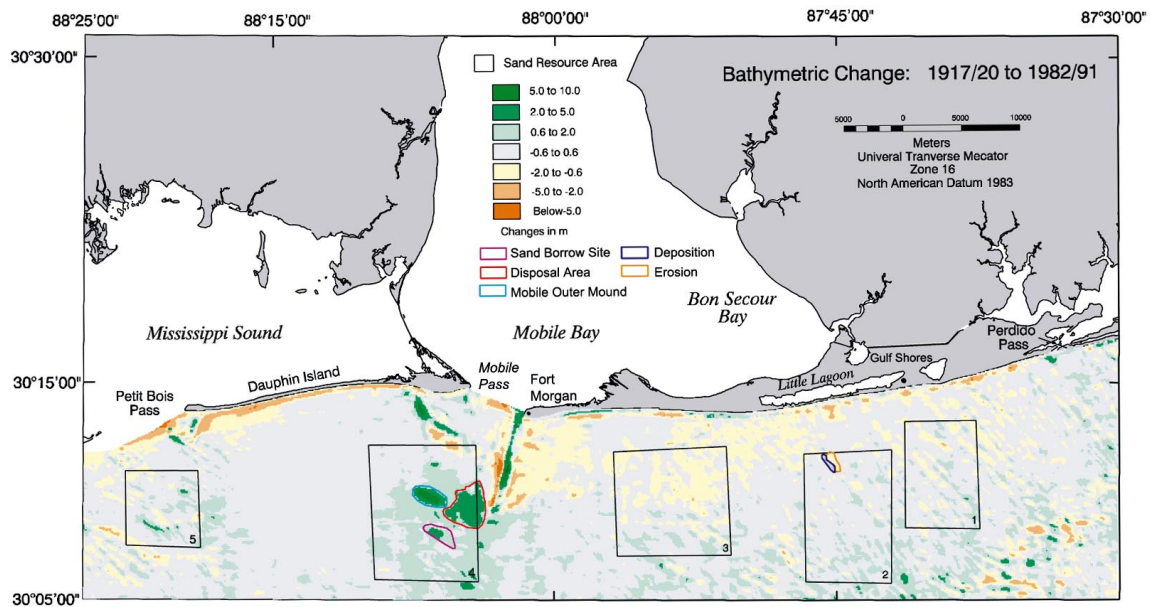

Figure 7.   Nearshore bathymetric change (1917/20 to 1982/91) for the Alabama coastal zone.

such, borrow sites at Areas 1, 2, and 3 are expected to fill with material adjacent to the excavated sites (the entire shelf surface south and east of Fort Morgan is at least 95% medium-to-fine sand; Table 1; McBride and Byrnes, 1995; Byrnes *et al.,* 1999). Sediment type in this region is relatively consistent and compatible for beach nourishment. The borrow site at Area 4, however, likely will fill with fine-grained sediment (*i.e.,* fine sand to clay) exiting Mobile Bay by natural processes and maintenance channel dredging and disposal. Because the potential local infilling rate plus sediment flux from Mobile Bay is substantially greater than shelf transport rates alone, the borrow site in Area 4 should fill faster than other borrow sites, limiting the likelihood for multiple dredging events from the same area.

Nearshore Sediment Transport Modeling. Sediment transport modeling results for the coast east of Fort Morgan and Dauphin Island indicate large variations in transport magnitude; however, the overall tendency along both shorelines is east-to-west littoral drift. For Gulf Shores and vicinity, longshore sand transport rates generally increased from west-to-east (50,000 to 150,000 m³/year; Figure 8) for seasonal simulations. Due to specific regions of wave focusing associated with seasonal wave characteristics, variations in sediment transport potential existed along the shoreline. For example, sediment transport calculations for spring and winter seasons indicated relatively high transport rates just west of Gulf Shores and lower transport rates along the western shoreline near Fort Morgan.

Along the Dauphin Island shoreline, greater seasonal variability in transport rates was evident. As a result of wave sheltering provided by Sand Island and offshore shoals on the Mobile Pass ebb-tidal delta, there was a marked decrease in annualized transport rates between the central portion of the island (120,000 m³/year) and its eastern terminus (<10,000 m³/year). Because the net direction of transport is from east-to-west, an increase in modeled transport rates from the east end of Dauphin Island to the center of the island created a net erosional trend. This result compares well with observed shoreline change between 1847/67 and 1978/81, where peak observed erosion, as well as peak computed erosion, occur at approximately the same location.

Benthic Environment

Water Column

During the May survey, bottom temperatures averaged 21.5°C. Bottom salinities averaged 31.1 ppt and ranged from 28.2 ppt in Area 3 to 33.9 ppt in Area 4. Dissolved oxygen averaged 3.16 mg/L and ranged from 1.22 mg/L (hypoxia) in Area 4 to 6.19 mg/L in Area 1. Bottom temperatures during
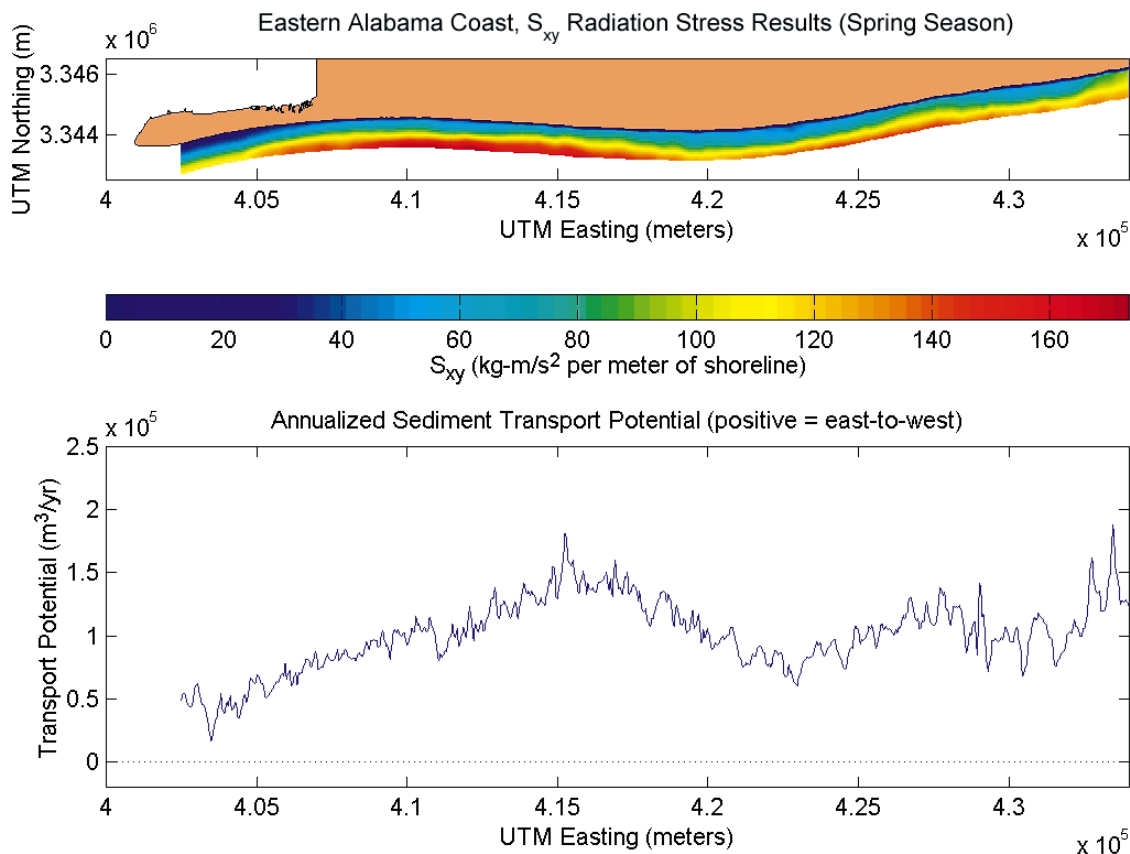

Figure 8. S_{xy} radiation stress values and annualized sediment transport potential for the spring season along eastern Alabama beaches.

the December survey averaged 16.9°C and ranged from 14.9°C in Area 2 to 18.5°C in Area 4. Salinities averaged 31.7 ppt and ranged from 31.2 ppt in Area 2 to 32.1 ppt in Areas 2 and 5. Dissolved oxygen values averaged 6.78 mg/L and ranged from 6.37 mg/L in Area 4 to 7.65 mg/L in Area 1.

Sediment Grain Size

Surficial sediments in Areas 1, 2, and 3 were primarily sand. In Area 1, all samples contained >95% sand with lesser amounts of gravel and no fines. All but two samples from Area 2 and two samples from Area 3 contained >96% sand with some gravel. Grain size was much more variable in Areas 4 and 5, where stations generally had substantial amounts of fines compared to Areas 1, 2, and 3. In Areas 4 and 5, <90% sand occurred in 43% and 45% of the samples, respectively.

Infauna

Infauna were more abundant during May (Table 2), when 64,613 individuals (70% of the project total) were collected. Numerical dominants were the gastropods *Caecum pulchellum* and *C. cooperi* that represented 24% and 9%, respectively, of all infauna collected during both surveys. *C. pulchellum* and *C. cooperi* occurred nearly exclusively in Areas 1, 2, and 3 during May (99.6% of all individuals) and December (99.8%) (Table 3). Areas 4 and 5 were numerically dominated by polychaetes during both surveys. Less than half (47%) of the 538 taxa censused were collected during both May and December. Most (70%) of the survey-restricted taxa were collected in May.

Mean number of infaunal taxa, individuals, and densities were higher at all areas during May than December (Table 2). Mean diversity (H') varied little among areas or between cruises. Mean values of H' ranged from 3.66 in Area 3 to 2.78 in Area 2 during May. Similarly, mean evenness (J') values varied little across areas and were consistently higher during the December survey than the May survey. Mean J' values ranged from 0.84 in Area 3 during December to 0.61 in Area 2 during May. Margalef's species richness (D) was consistently higher during May in all areas. The highest mean D

value (15.21) was recorded from Area 3 during May, and the lowest D value (6.85) was recorded for Area 4 during December.

Cluster analysis and MDS identified six groups (A through F) of stations that were similar with respect to species composition and relative abundance (Figures 2 and 9). These analyses revealed a strong temporal effect (Figure 9a). With the exception of Group E, which has stations from both surveys, station groups included samples collected exclusively during one of the two surveys (Figure 9b). Station Groups B and C contained the *Caecum*-associated assemblage from Areas 1, 2, and 3 during the May and December surveys, respectively (Figure 2). Group E stations were in Areas 4 and 5 during both surveys, and were dominated by polychaetous annelids with respect to both the number of taxa and overall abundance. Sediment grain size characteristics indicated that, except for Station Group E where the fine sediment fraction was greater relative to the other station groups, sedimentary regime was largely homogeneous within station groupings (Table 4).

Species typifying station groups (A through F) were determined by SIMPER analyses (Table 5). Species that most contributed to similarity patterns were: Group A—polychaetes *Spiophanes bombyx* and *Apoprionospio pygmaea*; Group B—*C. pulchellum, S. bombyx,* and *C. cooperi*; Group C—*C. pulchellum* and *C. cooperi*; Group D—amphipods *Eudevenopus honduranus* and *Protohaustorius* sp. C; Group E—polychetes *Paraprionospio pinnata, Nereis micromma,* and *Magelona* sp. H; and Group F—sipunculid *Phascolion strombi* and *N. micromma.*

The two-way ANOSIM test indicated significant differences in infaunal composition between surveys averaged over all sand resource areas (R = 0.556, p < 0.001) and between sand resource areas averaged over surveys (R = 0.516, p < 0.001). Pairwise comparisons of R among sand resource areas (Table 6) revealed that Area 1 and Area 5 were least alike (R = 0.904, p < 0.001), while Areas 4 and 5 were most similar with respect to assemblage composition (R = 0.104, p < 0.004).

Station groups defined by normal cluster analysis were analyzed using CDA to determine which environmental factors correlated best with the distribution of infaunal assemblages.

Table 2. *Summary of infaunal statistics by survey and sand resource area.*

	No. of Taxa		No. of Individuals		Density (individuals/m²)		H' Diversity		J' Evenness		D Richness	
Area	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation
						May 1997						
1	84	18	838	503	8,384	5,031	2.96	0.61	0.67	0.14	12.69	2.14
2	95	15	1,182	527	11,823	5,274	2.78	0.61	0.61	0.13	13.54	2.05
3	99	21	643	286	6,433	2,858	3.66	0.41	0.80	0.07	15.21	2.75
4	49	13	305	146	3,046	1,464	2.82	0.74	0.72	0.15	8.52	2.35
5	62	20	262	158	2,622	1,582	3.32	0.55	0.81	0.08	11.01	3.02
						December 1997						
1	67	20	571	389	5,714	3,891	2.97	0.59	0.71	0.13	10.63	2.97
2	57	18	345	187	3,447	1,867	2.93	0.36	0.73	0.08	9.69	2.40
3	47	11	184	83	1,839	831	3.20	0.25	0.84	0.06	8.99	1.53
4	35	12	145	73	1,449	725	2.83	0.41	0.81	0.09	6.85	1.90
5	36	15	123	60	1,229	603	2.85	0.59	0.81	0.12	7.27	2.51

Table 3. *Five most abundant infaunal taxa in grab samples collected during the May and December 1997 surveys.*

	May 1997			December 1997	
Area	Taxonomic Name	Count	Area	Taxonomic Name	Count
1	*Caecum pulchellum*	5,866	1	*Caecum pulchellum*	3,835
	Caecum cooperi	2,296		*Caecum cooperi*	1,019
	Bivalvia spp.	781		*Polygordius* spp.	1,001
	Spiophanes bombyx	600		*Eudevenopus honduranus*	503
	Tellina spp.	379		*Scoletoma verrilli*	268
2	*Caecum pulchellum*	9,183	2	*Caecum pulchellum*	1,737
	Caecum cooperi	3,059		*Caecum cooperi*	623
	Bivalvia spp.	1,440		*Polygordius* spp.	615
	Spiophanes bombyx	766		*Scoletoma verrilli*	357
	Tellina spp.	557		*Eudevenopus honduranus*	190
3	*Caecum pulchellum*	960	3	*Polygordius* spp.	321
	Caecum cooperi	851		*Caecum pulchellum*	278
	Spiophanes bombyx	772		*Caecum cooperi*	244
	Bivalvia spp.	717		Oligochaeta spp.	165
	Mediomastus spp.	574		*Mediomastus* spp.	132
4	*Paraprionospio pinnata*	1,680	4	*Branchiostoma* spp.	250
	Mediomastus spp.	729		*Armandia maculata*	209
	Spiophanes bombyx	243		*Nereis micromma*	201
	Apoprionospio pygmaea	202		*Mediomastus* spp.	199
	Magelona sp. H	198		*Magelona* sp. H	172
5	*Paraprionospio pinnata*	561	5	*Nereis micromma*	341
	Bivalvia spp.	225		*Mediomastus* spp.	211
	Mediomastus spp.	192		*Armandia maculata*	205
	Aricidea taylori	189		*Phascolion strombi*	103
	Polygordius spp.	149		*Aricidea taylori*	75

The first two CDA axes were used to analyze variability among those station groups identified as being similar with respect to species composition and relative abundance (Figure 10). The first CDA axis strongly correlated with survey (0.9867) (Table 7). Within surveys, the second CDA axis correlated well with percent sand (0.9024) and percent fine sediment (-0.8857). The class means of CDA variables for Station Groups A through F were plotted on CDA Axes 1 and 2 (Figure 10). This plot effectively displays separation of station groups with respect to measured environmental variables. Axis 1 was highly correlated with survey category, and Axis 2 was highly correlated with sediment grain size, contrasting samples with high proportions of fine sediments with those stations with high percentages of sand. Station Groups A and B separated from Groups C, D, and F along CDA Axis 1. Station Group E separated from all other station groups along CDA Axis 2, reflecting differences in sediment grain size. These first two CDA axes explained 99.2% of the variation in the group separation.

DISCUSSION

Physical Processes

Wave Transformation Modeling

Wave transformation results identified key areas of wave convergence, wave divergence, and shadow zones. For seasonal simulations, significant wave heights and angles experienced little variation seaward of the 15-m depth contour, landward of which the wave field becomes influenced by bathymetry. Seaward of Dauphin Island, wave heights were relatively consistent along the shoreline while the eastern end

of the island was protected from significant wave energy by a shadow zone produced by Sand Island and subaqueous shoals associated with the Mobile Pass ebb-tidal delta. DOUGLASS (1994) documented a similar trend with visual observations of wave height, period, and angle collected in 1991. Several areas of wave convergence were identified from simulations for offshore Dauphin Island, including those associated with Mobile Outer Mound, which focused wave energy near Sand Island during most seasons. Wave focusing caused by Mobile Outer Mound most likely resulted in an unnatural increase in erosion at Sand Island, and during a storm event may erode the protective island. Areas of wave convergence and divergence east of Fort Morgan primarily were caused by southwest-oriented shoals on the continental shelf. For the 50-year storm simulation, wave patterns were similar to normal seasonal results. An increase in wave height was substantial in many areas where wave convergence occurred. For example, Mobile Outer Mound concentrated 4.0- to 4.5-m wave heights on Sand Island during storm simulations.

Similar wave modifications were indicated for post-dredging simulations. Seaward of Dauphin Island, maximum wave height differences for seasonal simulations ranged from ±0.02 to 0.2 m. These maximum changes dissipated relatively rapidly as waves break and advance towards the coast. East of Fort Morgan, maximum wave height differences were slightly larger (±0.2 to 0.4 m) due to borrow site sizes and orientations, as well as their proximity to the shoreline. However, wave energy was dissipated as waves propagated toward the shoreline, and increases in wave height of 0.1 m or less were observed along the coast. During extreme wave conditions (*i.e.,* the 50-year storm), wave heights were modified
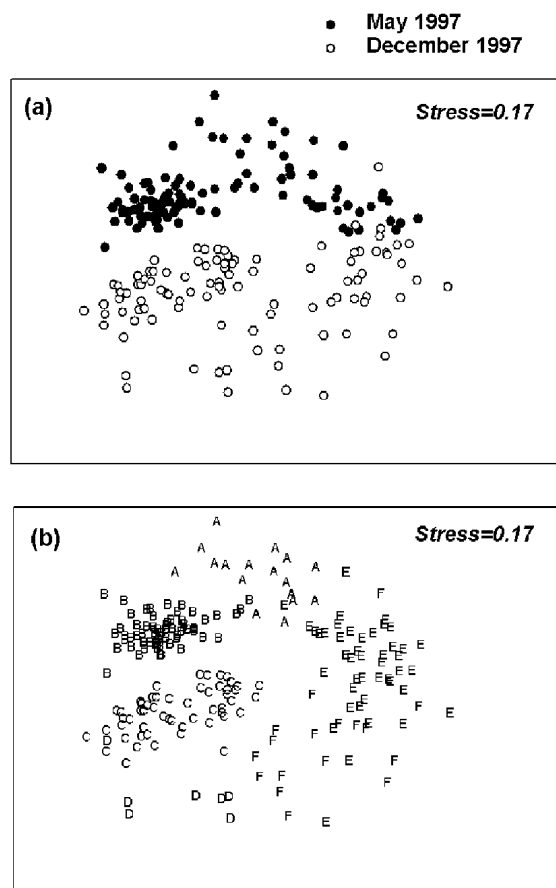
Figure 9.   Multidimensional scaling plots of infaunal samples collected during May and December 1997 at five offshore Alabama sand resources areas labeled by (a) survey and (b) groups determined from cluster analysis.

between ±1.5 and 2.0 m, suggesting a rather large change. However, much of this wave energy was dissipated before waves reached the coast. For example, wave height increases were less than 0.5 m along most of Sand Island for storm simulations. Overall, wave modifications caused by offshore sand extraction during seasonal and storm simulations were minimal.

Currents and Circulation

Throughout the study area, currents were predominantly parallel to shelf depth contours and driven by wind stress. Winds were shown to produce an approximate five-fold increase in current speed, with about 10 cm/sec currents during mild wind conditions to about 50 cm/sec during strong wind conditions. Frictional effects on the continental shelf modified currents as well; currents were strongest in the surface layer and weaker along the bottom and nearshore boundaries. Major bathymetric and shoreline features, such as the ebb-tidal shoals encompassing Sand Island and vicinity at the western margin of Mobile Pass, modified predominant flow directions. Less significant bathymetric features, such as shore-oblique

Table 4.   *Average percentages of gravel, sand, and fine sediments from samples collected within station groups determined from cluster analysis of infaunal samples.*

Station Group	Gravel	Sand	Fines
A	0.86	90.58	8.56
B	0.58	98.48	0.94
C	0.47	97.49	2.04
D	0.14	99.60	0.26
E	1.21	64.22	34.57
F	0.65	89.38	9.97

Table 5.   *Average abundance of infaunal species accounting for at least 50% of the within group similarity in Station Groups A through F.*

Group	Species	Average Abundance	Average Similarity
A	*Spiophanes bombyx*	17.18	4.90
	Apoprionospio pygmaea	14.35	4.38
	Paraprionospio pygmaea	22.00	3.53
	Phascolion strombi	7.76	3.26
	Tectonatica pusilla	3.53	2.55
	Nassarius albus	7.59	2.20
B	*Caecum pulchellum*	262.90	4.79
	Spiophanes bombyx	35.52	4.48
	Caecum cooperi	102.34	4.05
	Prionospio cristata	12.38	2.70
	Paraprionospio pinnata	10.92	2.10
	Eudevenopus honduranus	9.20	2.05
	Nephtys picta	8.00	2.02
	Acteocina candei	7.95	1.73
	Ervilia concentrica	10.00	1.60
C	*Caecum pulchellum*	108.30	5.27
	Caecum cooperi	34.78	4.91
	Eudevenopus honduranus	14.06	3.38
	Scoletoma verrilli	13.22	3.27
	Armandia maculata	5.37	2.27
	Spiophanes bombyx	3.00	2.00
D	*Eudevenopus honduranus*	9.43	7.56
	Protohaustorius sp. C	7.29	5.86
	Armandia maculata	6.71	4.52
	Metharpinia floridana	3.71	2.87
E	*Paraprionospio pinnata*	45.50	6.53
	Nereis micromma	11.82	6.13
	Magelona sp. H	10.05	5.63
	Scoletoma verrilli	6.82	3.85
F	*Phascolion strombi*	8.71	7.12
	Nereis micromma	11.12	4.93
	Armandia maculata	12.29	3.32
	Tectonatica pusilla	2.12	2.66

Table 6.   *Pairwise analysis of similarities tests comparing infaunal assemblage composition. Significance levels (in parentheses) are based on comparisons of actual R statistics with a distribution generated from 999 random permutations. *(p<0.001), **(p<0.005).*

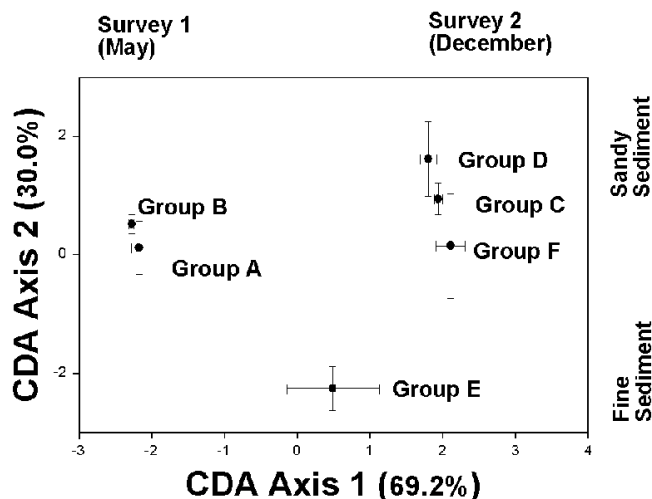| Sand Resource Area	1	2	3	4
1				
2	0.279*			
3	0.437*	0.228*		
4	0.742*	0.655*	0.505*	
5	0.904*	0.820*	0.642*	0.104**

Figure 10. Means (± 95% confidence intervals) of canonical variables for infaunal Station Groups A through F plotted on Canonical Discriminant Analysis (CDA) Axes 1 and 2.

Table 7. *Correlations between the first two axes of canonical discriminant analysis and environmental variables recorded for Station Groups A through F.*

Variable	Axis 1	Axis 2
Survey	0.9867	0.1619
% Gravel	−0.0296	−0.2906
% Sand	−0.1382	0.9024
% Fines	0.1404	−0.8857
Water Depth	−0.0899	0.6118

shoals prevalent east of Mobile Pass or Mobile Outer Mound located in Area 4, had little effect on large-scale circulation.

For Areas 1, 2, and 3, surface shape is rough with numerous ridges and swales. Circulation in the region appeared to be affected by bottom friction, but the influence was recognized as weaker flow at the bottom and nearshore areas than at the surface. Because sand resource areas east of Mobile Pass contain numerous ridges and swales, it is doubtful that alteration of a single ridge would significantly impact bottom roughness or have measurable impact on regional current flow.

Currents in Area 4 were influenced primarily by Sand Island, which produced a significant steering effect to divert flow along a general northwest/southeast axis, parallel to bathymetric contours. ADCP field surveys showed highly localized bottom flow vectors influenced weakly by the presence of Mobile Outer Mound. Adjacent flow vectors did not appear to be influenced by the mound, but they were directed along depth contours, consistent with prevailing flow through the region. This suggested that small-scale bathymetric irregularities, such as a sand borrow site, while producing a localized effect on currents, is not expected to impact prevailing or ambient flow characteristics.

Sediment Transport

Borrow Site Infilling. Small changes in sediment transport at borrow sites are expected after sand mining is completed. Given the water depths and geometries at proposed borrow sites, minimal impacts to waves and natural sediment transport processes are anticipated during infilling. Volume and type of sediment that replace excavated sand from borrow sites will fluctuate based on location, time of dredging, and storm characteristics following dredging episodes. However, infill sediment is expected to reflect surface sediment texture at adjacent ridge and swale deposits.

Longshore Sediment Transport. For average annual conditions, mean longshore sand transport rates landward of borrow sites in Areas 1, 2, and 3 are approximately equal. Along the eastern portion of Dauphin Island (landward of Area 4), transport rates were estimated to be approximately 35% of the rates associated with the shoreline east of Fort Morgan. The absolute value of the mean difference between existing and post-dredging conditions generally decreased east-to-west, with a maximum difference of approximately 8,000 m³/year (about 8%) along the shoreline influenced by dredging in Area 1. Because the net longshore sediment transport rate predicted landward of Area 4 was relatively low (approximately 33,000 m³/year; similar to DOUGLASS [1994]), the percentage difference between existing and post-dredging conditions was greatest for this site (about 10%). Results from analyses of a 50-year event indicated similar trends.

KELLEY *et al.* (2004) developed an analytical approach for quantifying the significance of potential physical environmental impacts associated with offshore sand mining. The approach incorporates an analysis of nearshore wave transformation and wave-induced longshore sediment transport for existing and post-dredging conditions relative to temporal and spatial variations in the local wave climate. Based on wave transformation results and the natural variability of normal wave climate for coastal Alabama, predicted changes in longshore sediment transport rates resulting from offshore sand mining (up to 8 to 10% of existing conditions) are expected to have minimal impact along the shoreline.

Benthic Environment

Infaunal assemblages within the five sand resource areas included common taxa expected for similar sedimentary environments and water depths in the northern Gulf of Mexico (DAMES & MOORE STAFF, 1979; SHAW *et al.,* 1982). Statistical representation of the assemblages by univariate and multivariate analyses helped reduce the complexity inherent in such samples. Areas were effectively discriminated with respect to assemblage composition and basic patterns were linked to environmental variables. Understanding statistical properties of assemblages provides a strong basis for designing monitoring programs to evaluate impacts and recovery of future dredging projects in the areas.

Univariate and multivariate techniques used in our analyses actually provided differing perspectives on infaunal assemblages in the five areas. Univariate approaches such as H', J', and D that collapse all of the species-level information into a single index gave no indication of faunal composition

in different areas. For example, mean values of *H′* and *J′* were very similar among sand resource areas and between surveys, giving the impression that infaunal assemblages in all areas were similar. In contrast, multivariate analyses revealed clear differences in assemblage composition between eastern (1, 2, and 3) and western (4 and 5) areas, as well as differences between surveys. This disparity in results from univariate and multivariate analyses of the same data set is a common finding with benthic assemblages (WARWICK and CLARKE, 1991). Although multivariate methods effectively uncover patterns from complex sets of multi-species data, results generated in the form of ordination diagrams cannot always be used to clearly demonstrate impacts. Single index statistics, despite their shortcomings, are better suited for documenting stress or direction of change. Therefore until a better method emerges, future monitoring and impact analyses should employ both univariate and multivariate approaches (WARWICK and CLARKE, 1991).

The field surveys also provide data properties that will greatly assist managers in designing monitoring programs to assess the impacts and recovery of infaunal assemblages following any future mining projects that may occur within the five areas. These properties (*e.g.,* inter-sample variability) can be used to calculate samples sizes necessary to achieve desired levels of precision, statistical power, or species accumulation. Such information often is lacking in the design phase of impact or monitoring studies.

Characterization of existing infaunal assemblages and their statistical properties provide a good basis for designing and analyzing future studies. Analyses of infaunal composition, distribution, and abundance will to some extent serve as a foundation for evaluating impacts and recovery by similar taxa in similar environments at locations other than the Alabama shelf.

Infaunal species assemblages exhibited a marked change from east to west in the study area. Overall, eastern sand resource areas (1, 2, and 3) were similar in assemblage composition and different from western areas (4 and 5), which were most similar in pairwise comparisons of all sand resource areas. Differences were most pronounced comparing Area 1 to Area 5. This broad-scale zonation is most likely due to the influence of discharges from Mobile Bay, which predominantly move toward the west-southwest along the inner shelf (DINNEL *et al.,* 1990; STUMPF *et al.,* 1993). River discharges affect adjacent shelf environments by changing salinity, temperature, nutrients, and other water column variables, as well as transporting fine particulates to the seafloor. These changes result in an offshore hydrographic structure resembling estuarine conditions (BLANTON and ATKINSON, 1978), which affects exploitation by infauna (HANSON *et al.,* 1981; TENORE, 1985). There also was spatial variability of infauna within resource areas, primarily in Areas 4 and 5. Homogeneous sand and infauna were characteristic of eastern areas, whereas for western areas, sand station assemblages were distinct from fine sediment (silt and clay) assemblages, regardless of survey season. Sand environments on the shelf east of Mobile Pass yielded assemblages that differed from sand assemblages west of Mobile Pass, suggesting that bay discharge was a prime determinant of broad spatial distributional patterns. In areas west of Mobile Pass, sediment type was a finer scale factor influencing habitat suitability for infauna, as illustrated by differences between sand and fine sediment assemblages. Because outwelling from Mobile Bay rarely flows to the east (DINNEL *et al.,* 1990; STUMPF *et al.,* 1993), assemblage differences between the east and west Alabama shelf are likely to be a persistent feature of benthic community structure in the area. RAKOCINSKI *et al.* (1998) also found alongshore faunal gradients in beach and shallow subtidal benthos when comparing areas just outside the eastern and western geographic boundaries of this study.

Between-survey differences in assemblage composition were striking, particularly fewer taxa overall and lower abundance during December. Like other benthic community parameters in open shelf systems, species richness varies on multiple temporal and spatial scales, and little is known of the manner and degree to which local patterns are influenced by broad geographic richness patterns (GRAY, 2002). Reasons for the strong temporal patterns observed in this study may be due to a variety of causes, including variations in reproductive times and subsequent settlement by component species. Sand bottoms across the area yielded different assemblages between surveys primarily because sand generalists (taxa that were collected from sand stations across the study area) either were greatly diminished in abundance or completely absent during December. Conversely, assemblages at most stations with measurable amounts of silt and clay (Group E stations) did not change with survey. Highly abundant taxa in fine sediment areas, such as *Magelona* sp. H (=*M.* cf. *phyllisae*), *Mediomastus* spp., and *Paraprionospio pinnata,* are widespread species also characteristic of northern Gulf estuaries (GASTON *et al.,* 1995). These species are components of a group of opportunistic infauna with high reproductive capacity and dispersal ability (GRASSLE and GRASSLE, 1974; GASTON and EDDS, 1994), also commonly occurring inshore to mesohaline (18 to 5 ppt) environments (MCBEE and BREHM, 1982; GASTON and EDDS, 1994; RUTH *et al.,* 1994; GASTON *et al.,* 1995). Such taxa tend to be surface and sub-surface deposit feeders adapted to living in fine sediments, and are able to rebound from periodic perturbations, such as summer hypoxia (HOLLAND, 1985; GASTON and EDDS, 1994). In fact, some near-bottom dissolved oxygen levels in Area 4 were hypoxic (< 2.0 mg/L) during the May survey. The relative environmental harshness of western areas was reflected in fewer taxa relative to Areas 1, 2, and 3 during May and December. Infaunal assemblages in Areas 4 and 5 thus include opportunistic species that colonize perturbed habitats in general.

Knowledge of faunal component lifestyles allows some predictions of dredging impacts and subsequent recolonization and recovery of community composition (NEWELL *et al.,* 1998). Although this study provides only benthic community characterization, review of previous dredging studies can be used to infer offshore mining effects on infaunal community patterns in the study area. This is the case with respect to seasonal timing of dredging, as well as disturbances from sand removal, including bathymetric form and depth of substratum changes.

Documented impacts of sand mining are varied with re-

spect to infaunal recolonization and recovery at offshore dredged sites, depending particularly on examined community indices. While levels of abundance and diversity may recover within 1 to 2 years in certain cases (*e.g.,* SALOMAN *et al.,* 1982; JOHNSON and NELSON, 1985), it may take many years to recover in terms of sediment characteristics and species composition. WILBER and STERN (1992) reexamined infaunal data by grouping species into functional groups called ecological guilds based on similarities in feeding mode, locomotory ability, and sediment depth occurrence. They concluded that infaunal communities recolonizing borrow sites may remain in an early successional stage for 2 to 3 years or longer as opposed to being completely recovered in shorter time frames.

Because infaunal assemblages are affected greatly by sedimentary habitat, the recovery time of benthic assemblages can depend in large measure on the degree and duration of sediment alteration from sand borrowing (VAN DOLAH, 1996). Changes in sediment characteristics in borrow sites may occur because sediment texture of the newly exposed substratum is different from the removed sediments, or because the excavated site becomes a reservoir of fine sediments and organic material. A key assumption when supposing short-term (*i.e.,* within 2 years) mining-related effects is that dredging a pronounced bathymetric depression would be avoided. Many studies show decreases in mean grain size, and in some cases, increases in silt and clay content in borrow sites following dredging (NATIONAL RESEARCH COUNCIL, 1995), particularly in relatively steep bathymetric depressions sometimes formed by dredging.

In addition to the shape of topographic features created by offshore sand mining, reworking of exposed sediments is an important process in benthic recovery after dredging because it promotes diffusion of dissolved oxygen into soft substrata exposed during dredging. KENNICUTT *et al.* (1995) found that shelf sediments of the Alabama coastal region are continually reworked to 60-m depths, particularly due to storms and through influxes of terrestrial material associated with river discharges. The eastern portion of the study area apparently is not a fine-grained depositional environment, given the relative lack of fine sediments, and the western portion of the study area is greatly influenced by Mobile Bay discharges. Sediment reworking may be less important for assemblage recovery processes west of Mobile Pass compared to eastern areas because opportunistic taxa in Areas 4 and 5 presumably are better adapted to environmental stress. Physical dynamics of the study area would promote biological recovery of dredged sites through sediment reworking. Moreover, because sandy sediments on the eastern Alabama shelf are vertically uniform, sediments exposed by mining would be similar to those removed, thus allowing a similar suite of taxa to colonize dredged sites.

Early-stage recruitment of defaunated sediment has been found to occur rapidly in coastal systems (GRASSLE and GRASSLE, 1974; MCCALL, 1977; SIMON and DAUER, 1977; RUTH *et al.,* 1994). Dredged sites on the Alabama shelf would be colonized by opportunistic infauna relatively quickly, particularly taxa such as *Mediomastus ambiseta* (RUTH *et al.,* 1994), and *Magelona* sp. H and *Paraprionospio pinnata* (GAS-

TON and EDDS, 1994). Timing to avoid dredging during the peak recruitment period of warm months would facilitate more rapid faunal recovery. It is likely that recolonization and recovery processes would differ between areas east and west of the mouth of Mobile Bay. Dredged sites in Areas 4 and 5 would be expected to recover more quickly than eastern areas because of the opportunistic nature of numerically dominant infauna west of the bay mouth. Sediment and infauna in eastern areas are homogeneous, which promotes benthic recovery after dredging through immigration of fauna from adjacent non-dredged areas (VAN DOLAH *et al.,* 1984), complementing colonization via larval recruitment. Preservation of non-dredged areas throughout an offshore borrow site has been cited as a factor potentially contributing to more rapid community recovery after dredging (JUTTE *et al.,* 2002). It is important to note that the nature of the reestablished community would not necessarily return to pre-dredged species composition. While levels of diversity and abundance may be reached or exceeded within a relatively short time after dredging, the pertinent goal of recovery success is for infaunal assemblages to become equivalent to nearby non-dredged areas within a relatively brief interval after dredging. Because assemblages vary over time, efforts to ascertain recovery success can be confounded by natural variability, and so overall temporal changes in community parameters of non-dredged areas should be taken into account.

CONCLUSIONS

Literature and data collected, analyses performed, and simulations conducted for this study indicate that sand mining at sites evaluated on the Alabama OCS should have minimal environmental impact on fluid and sediment dynamics. Although physical environmental impacts resulting from potential sand dredging alternatives tested in this study have been identified through wave and sediment transport simulations, under normal wave conditions, the maximum change in sand transport dynamics is about 8 to 10% of existing conditions. Based on wave transformation results and natural variability of the normal wave climate for coastal Alabama, predicted changes in longshore sediment transport rates resulting from offshore sand mining are expected to have minimal impact along the shoreline. Although changes during storm conditions illustrated greater variation, the relative impacts were similar to non-storm conditions. Furthermore, the ability of models to predict storm wave transformation and resultant sediment transport is less certain than for normal wave conditions.

Impacts to the benthic community are expected from physical removal of sediments and infauna. Based on previous studies, and assuming that dredging does not produce deep pits causing very fine sediment deposition or hypoxic or anoxic conditions, levels of infaunal abundance and diversity may recover within 1 to 3 years, but recovery of species composition may take longer. Offshore areas west of Mobile Bay can be expected to recover more quickly than areas seaward and east of Fort Morgan because of opportunistic life history characteristics of numerically dominant infauna.

ACKNOWLEDGMENTS

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